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HEAT TRANSFER INTENSITY IN THE CONDENSATION SECTION OF A HEAT PIPE

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16. Abstract

A dimensionless equation for calculating the heat transfer intensity in the condenser of a heat pipe is derived from dimensionless analysis of the fundamental convective heat transfer equations. The influence of vapor pressure on the heat transfer intensity in a heat pipe condenser is determined and experimental condenser heat transfer data are generalized.

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HEAT TRANSFER INTENSITY IN THE CONDENSATION SECTION OF A HEAT PIPE

V. I. Sasin and A. I. Shelginskiy[1]

According to the operating principle of a heat pipe, its heat transfer capacity is determined by both the hydrodynamic vapor and liquid flows and by the rate of radial heat transfer in the evaporator and condenser, which determines the temperature drop through the length of the pipe [1]. The thermal resistance of the pipe, thermal conductivity of the wet wick, temperature jumps during phase transitions, etc., in addition to external heat exchange conditions, influence the magnitude of this drop. /436*

If the performance characteristics of the heat pipe operating in the evaporating mode at moderate steam pressures can be calculated on the basis of a simple model that considers only the thermal conductivity of the wet wick [2], then in the boiling mode, and also at low steam pressures this problem is considerably more complicated because of the greater importance of the rate of heat exchange between the moving steam and liquid at the phase interface.

We will examine the heat transfer process in the condenser of a heat pipe, using the fundamental equations of convective heat exchange.

We assume that the motion of the liquid in the wick is one-dimensional and may be described by the D'Arcy law of flow liquid in porous materials, when the equations of motion, energy and continuity for the condensor acquire the forms:

$$-\frac{dP_v}{dz} + 2\sigma \frac{d}{dz}\left[\frac{1}{R_{cap}(z)}\right] - \frac{\mu_1}{K\rho_1}[\rho_1 W_1(z)] = \frac{1}{2\rho_1}\cdot\frac{d}{dz}[\{\rho_1 W_1(z)\}^2], \quad (1)$$

$$i_1 \frac{d}{dz}[\rho_1 W_1(z)] + \frac{Q}{\varepsilon F_f L_c} = \frac{\pi d_v}{\varepsilon F_f} i_v G_v, \quad (2)$$

$$W_v \frac{\pi d_v^2}{4} \rho_v = W_1 \varepsilon F_f \rho_1, \quad (3)$$

[1]Moscow Order of Lenin Power Engineering Institute.
*Numbers in the margin indicate pagination in the foreign text.

We convert these equations to the dimensionless form. As the determining dimension we will use the radius of the vapor space, and as the determining velocity we will use the velocity of the vapor at the interface of the two phases. Then /437

$$W_1 = \frac{W_1}{U_w} = \frac{\alpha(t_1 - t^c_{wa})F^2_c\rho_v}{rW_1(\rho_1 \varepsilon F_f)^2}. \quad R_{cap} = \frac{R_{cap}}{R_v}; \; z' = \frac{z}{R_v}. \tag{4}$$

By substituting (4) into equations (1), (2) and (3) and arranging the parameters so as to obtain dimensionless complexes, we find that heat exchange in the condenser of the heat pipe depends on the following factors:

$$St = f\left(Re_r: N_p: K; Pr_1: \frac{R_{cap}}{R_n}; \frac{R^2_n}{k}; \frac{F_c}{\varepsilon F_f}\right). \tag{5}$$

where $Re_r = \frac{R_h U_w}{\nu_v}$ is the Reynolds number; $N_p = \frac{m\sigma}{P_v R_v}$ is a dimensionless complex that considers the ratio of forces of surface tension to forces of pressure; m is the meniscus form factor; $K = \frac{r}{c_{p_1}(\bar{t}_1 - t^c_{wa})}$ is the Kutateladze number;

$St = \frac{a}{c_{p_1}\rho_1 W_1}$ is the Stanton number; $Pr_1 = \frac{\nu_1}{a}$ is the Prandtl number;

$\alpha = \frac{Q}{F_c(\bar{t}_1 - t^c_{wa})}$ is the coefficient of heat exchange in the condenser of the pipe.

Analysis of expression (5) shows that heat exchange in the condenser of a heat pipe is influenced by the thermal power which the pipe transmits, the vapor pressure at which this power is transmitted, the physical properties of the working liquid and the geometric characteristics of the heat pipe and wick.

An equation that connects the dimensionless complexes entering in (5) was derived on the basis of generalization of experimental data on heat exchange in the condensers of heat pipes with water and alcohol as heat transfer agents:

$$StN^n_p Re_r = CK^{0.4}Pr^{1.3}. \tag{6}$$

Here n = 0.48 for $N_p < 1.1 \cdot 10^{-3}$ and n = 0.833 for $N_p > 1.1 \cdot 10^{-3}$; C is a constant that includes the geometric characteristics of the heat pipe and wick, which enter in (5). The physical constants of the working liquid for calculating the criteria were determined for temperature halfway between the temperature of the vapor and the temperature of the condenser walls. The heat of vaporization and surface tension of the liquid were determined for the vapor temperature. /438

The effect of the vapor pressure on the rate of heat exchange in the condenser is illustrated in Figure 1.

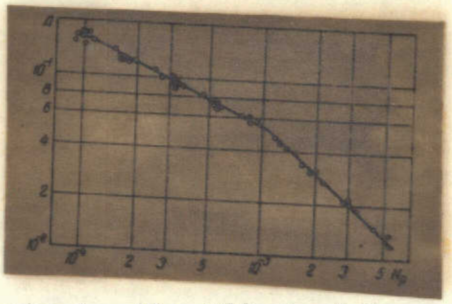

Figure 1. The Effect of Vapor Pressure on Heat Exchange Rate in Condenser of Heat Pipe. L = 470 mm; L_c = 100 mm; d = 19.5 mm; $A = \frac{StRe_2}{CK^{0.4}Pr^{1.3}}$.

As seen by the figure, the rate of heat exchange in the condenser of a heat pipe changes sharply when $N_p = 1.1 \cdot 10^{-3}$, which corresponds to the vapor pressure of $0.11 \cdot 10^5$ n/m^2. The reason for this is that when the vapor pressure decreases the coefficient of vapor condensation decreases and the thermal resistance of phase transition increase:

$$R_f = \frac{t_v - t_{sur}}{q} \qquad (7)$$

where

$$q = \frac{Q}{\pi d_v L_c}.$$

The generalized experimental data on heat exchange in the condenser of a heat pipe with a diameter of 19.5/0.25 mm are presented in Figure 2. The overall length of the pipe is 470 mm, the length of the condenser is 100 mm and the diameter of the vapor channel is 17.7 mm.

The wick, consisting of 3 layers of brass screen with an average cell dimension of 0.2 mm, was 0.65 mm thick and its permeability was $2.02 \cdot 10^{-10}$ m^2.

The continuous line in Figure 2 corresponds to equation (6), and the broken lines bound the range in which the deviation of the experimental data from the theoretical dependence does not exceed 20%.

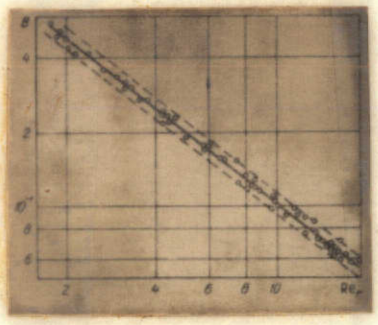

Figure 2. Generalized Experimental Data on Heat Exchange in Condenser of Heat Pipe. L = 470 mm; L_c = 100 mm; d = 19.5 mm; $B = \frac{StN_p^n}{CK^{0.4}Pr^{1.3}}$ where n = 0.833 for $N_p > 1.1 \cdot 10^{-3}$; n = 0.48 for $N_p < 1.1 \cdot 10^{-3}$.

Symbols

P, pressure in N/m^2; σ, surface tension in N/m; z, axial coordinate in m; R, radius; μ, viscosity in n sec/m^2; K, permeability in m^2; ρ, density in kg/m^3; W, axial velocity in m/sec; i, enthalpy in joules/kg; ε, porosity; F, area in m^2; L, length in m; G, mass flow rate per unit area in $kg/m^2 \cdot sec$; r, heat of vaporization joules/kg; c_p, heat capacity in joules/kg·degree; t, temperature in °C; Q, heat flux in watts; U, radial velocity in m/sec; d, diameter.

Subscripts: 1, liquid; v, vapor; sur, surface; f, wick; cap, capillary; c, condenser; w, liquid-vapor interface.

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